Concluding Remarks

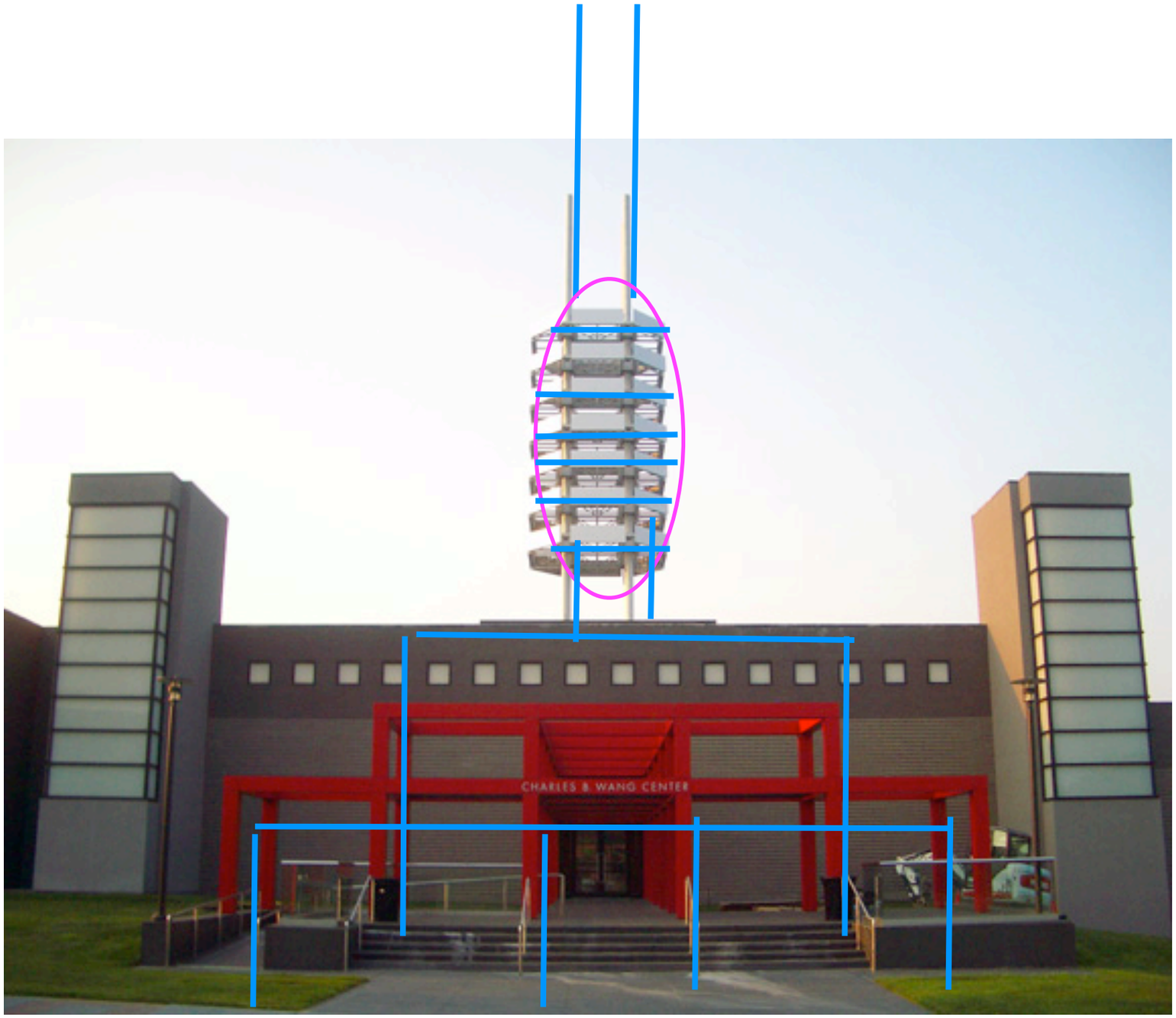
Stony Brook/ BNL

Eric Laenen

UNIVERSITEIT VAN AMSTERDAM
NIKHEF
University of Utrecht

Beautiful venue

Beautiful venue



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- Home of gauge theory
  - Yang-Mills theory, QCD, Standard Model, (Super) gravity

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  - academics, or ...?

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- "Berkeley of the East"
  - academics, or ...?
- A wonderful place for PhD student. Atmosphere fits here
  - (opening lecture)
  - open, many discussions, so much to learn, as at this meeting

Stony Brook, 1990

Overview

47 talks, XII sessions

Very impressive new results, methods, ideas, codes..

Broadening range of topics

- MC, and NLO
- QCD NLO/NNLO
- QCD NLL/NNLL
- EW/Susy corrections, Higgs physics, New physics
- NLO codes/libraries
- Factorization, EFT, SCET
- PDF's, heavy flavors

A reader's digest
might be useful

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Common theme: particle scattering

Popular Scattering

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16:05 NLO Corrections for High Multiplicity Jet Observables (25') Walter Giele (*FNAL*)

16:30 Concluding Remarks (25') Eric Laenen (*Nikhef*)

At least here the Dutch are in the finals

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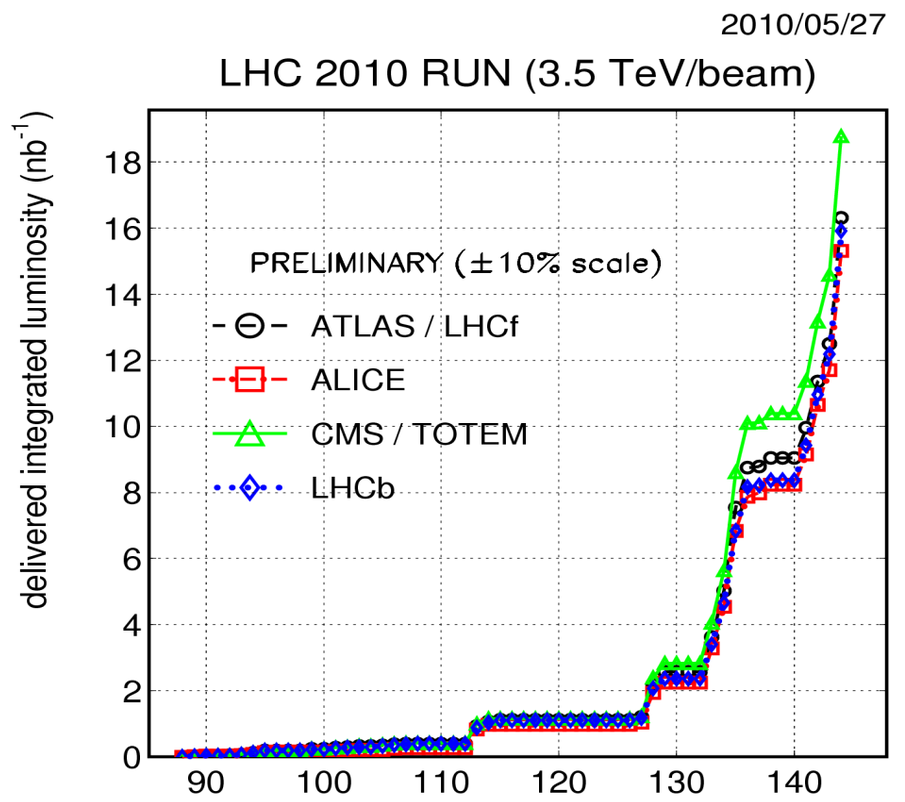
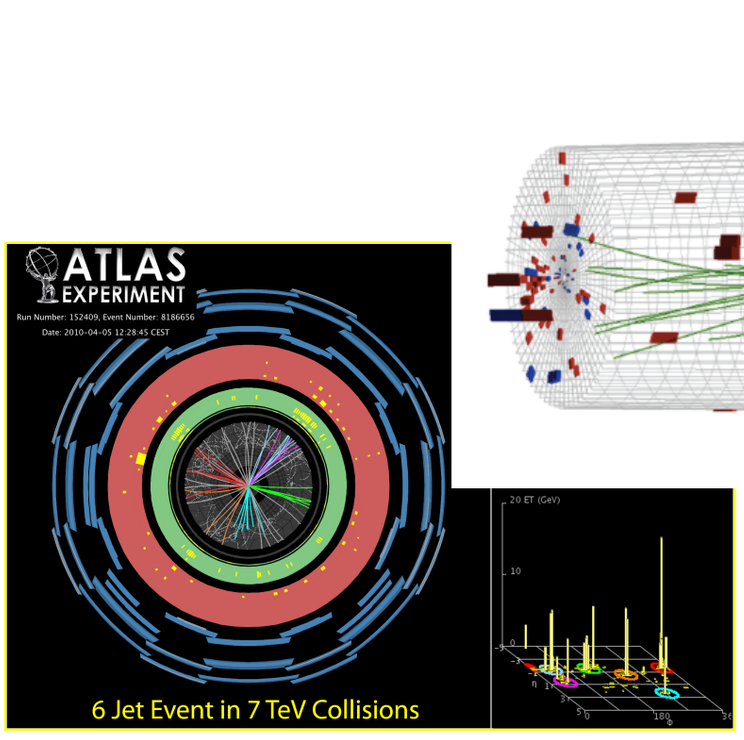
Slightly less popular, and less expensive scattering:

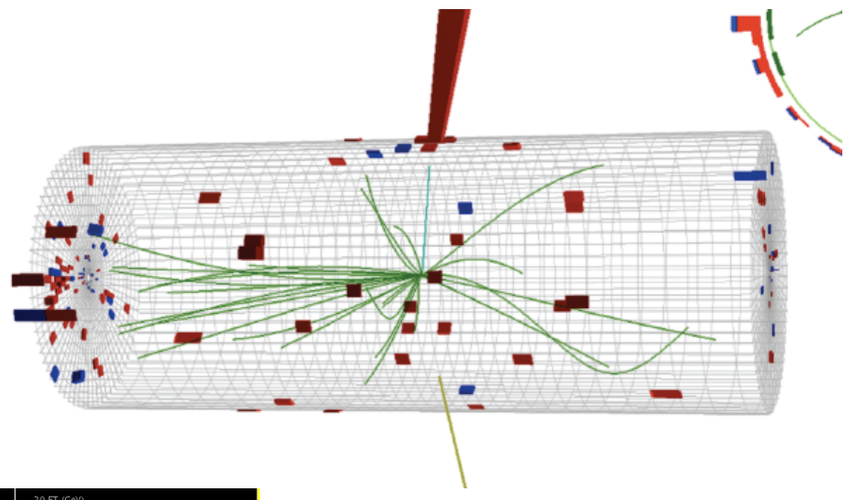
LHC! Finally here!

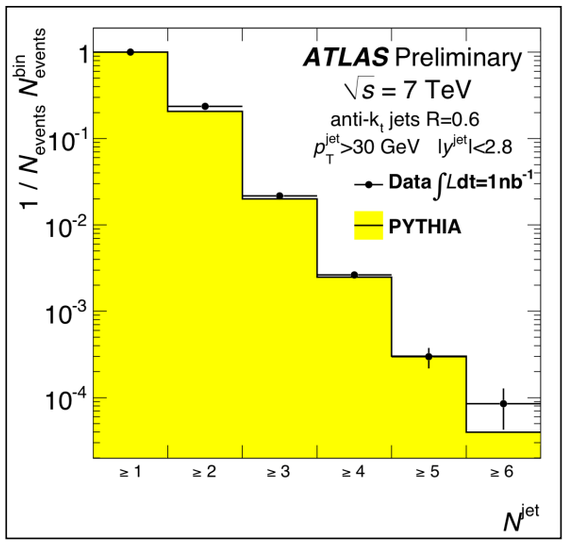
Mariotti

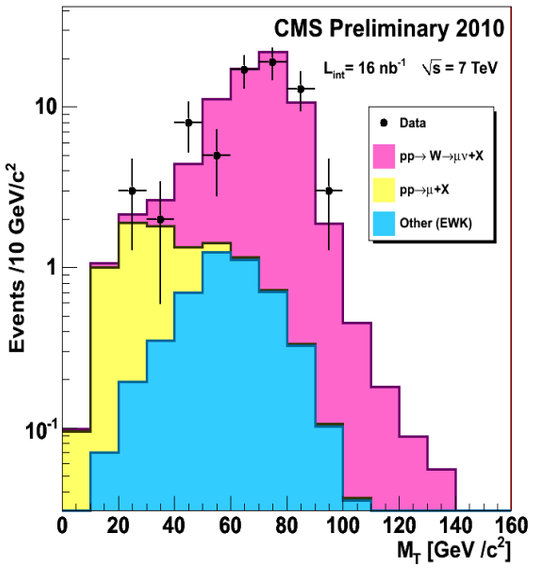
- Steep learning curve for beam
  - focus now on getting nominal bunches → 10e32
- Physics at 20/nb
  - W's, Z's, jets, (lots of resonances), UE, diffraction
    - ✓ 3 tops/experiments?
- Detectors well-understood, run at high efficiency
- Data processing (Grid) going very well







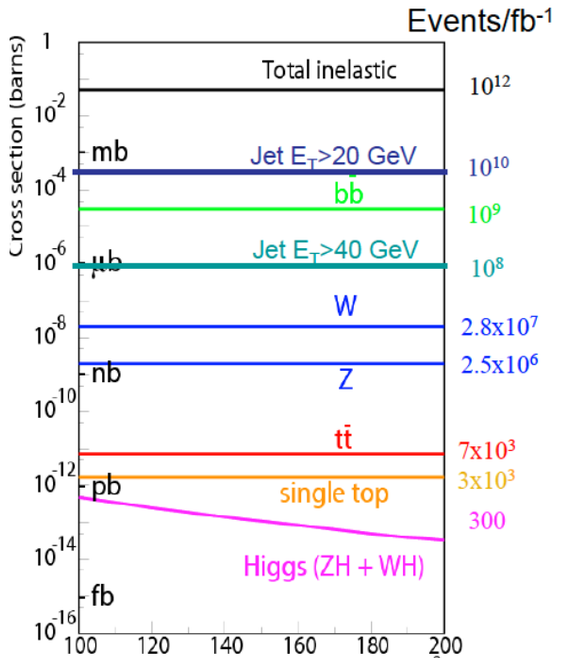


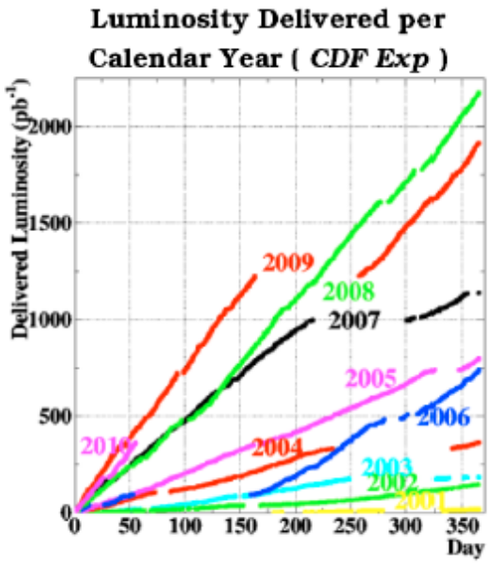


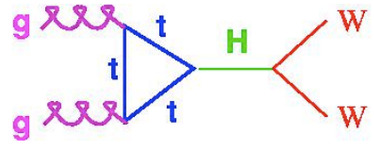
Tevatron! Still very much here!

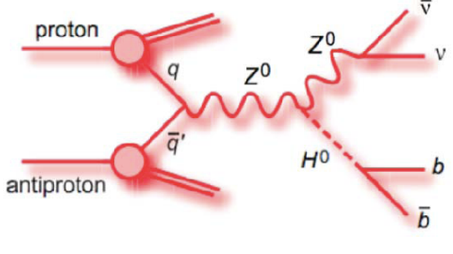
Wood

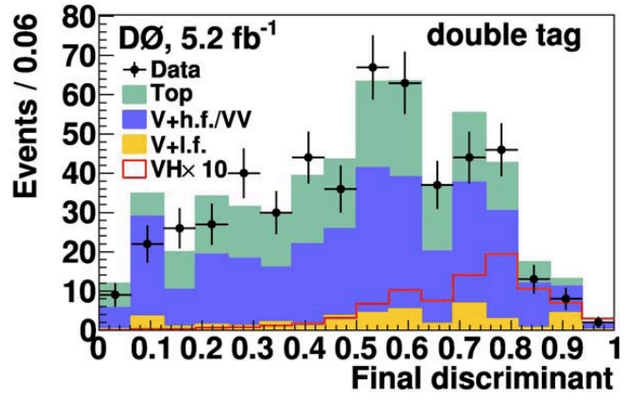
- Top
  - Vtb = 0.88 +- 0.07
  - CDF l+jets: m(top) = 172.8 +- 1.2 GeV
  - σ(tT) normalized to DY, < 7% uncert.
- EW
  - m(W) = 80.42 +- 0.031
  - dibosons
- QCD
  - jets, jets+
- B_s
  - like-sign dimuon asymmetry in D0: 3.2σ
- Higgs
  - intermediate mass H → WW, first exclusion since LEP
  - light Higgs: ETmiss, b-tags, discriminant











ILC, will it be here?

Peskin

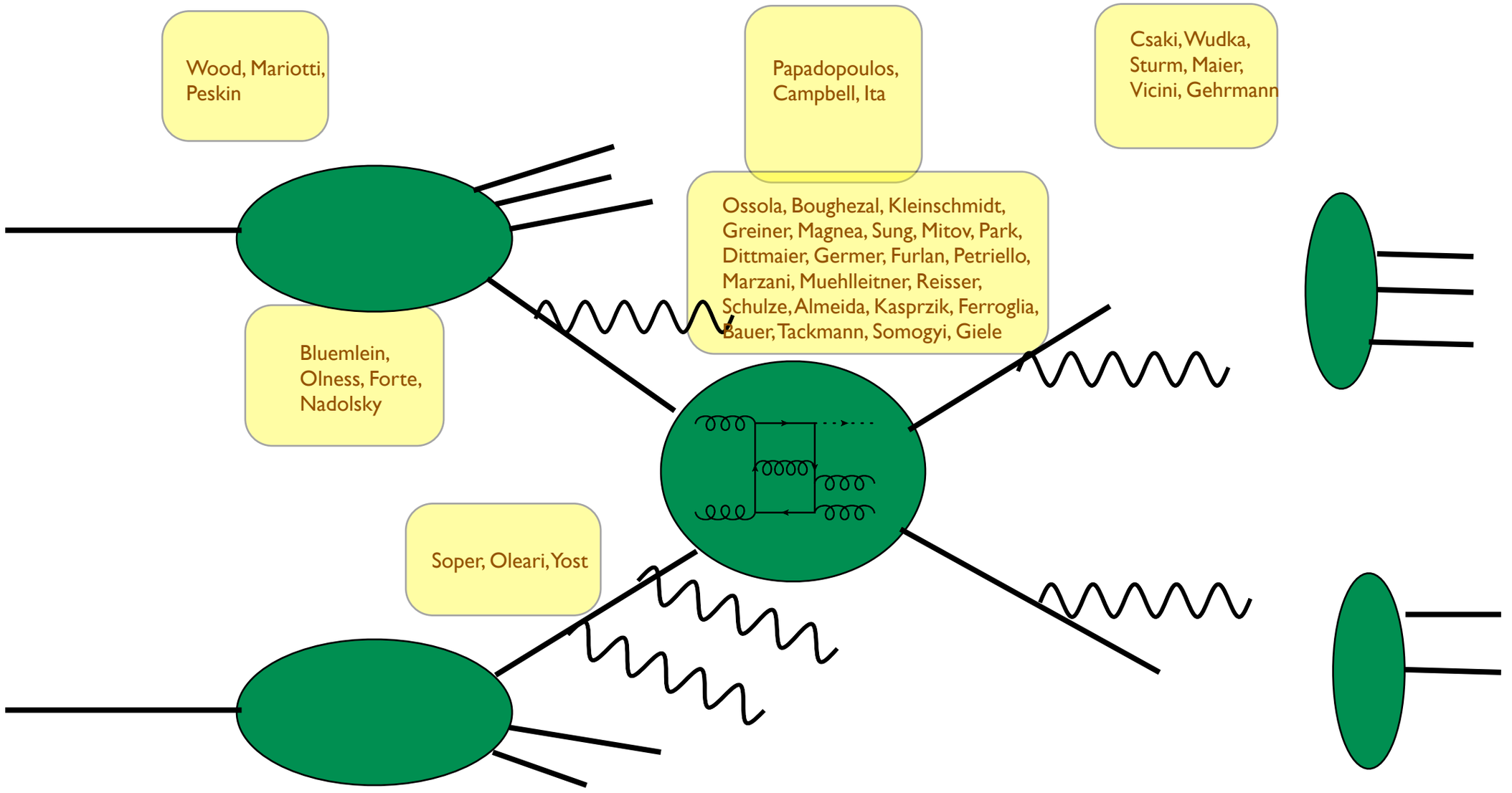
- Next machine, by global consensus
- Must answer LHC questions
  - SM: Higgs, measure couplings with precision
  - BSM: characterize uniquely, in particular DM
- For (Loopfest) theorists, primary mission accomplished
  - next: top MC, multi-jets
- When, how much?
  - Urgency less felt
  - Cost comparable to LHC [less/year is more..]
  - *Vincit qui in labore persistit*

RDR vs ICFA Parameters

- E_{cm} adjustable from 200 – 500 GeV
- Luminosity → $\int Ldt$ = 500 fb^{-1} in 4 years
- Ability to scan between 200 and 500 GeV
- Energy stability and precision below 0.1%
- Electron polarization of at least 80%
- The machine must be upgradeable to 1 TeV

Barish, ILC2010

You are here!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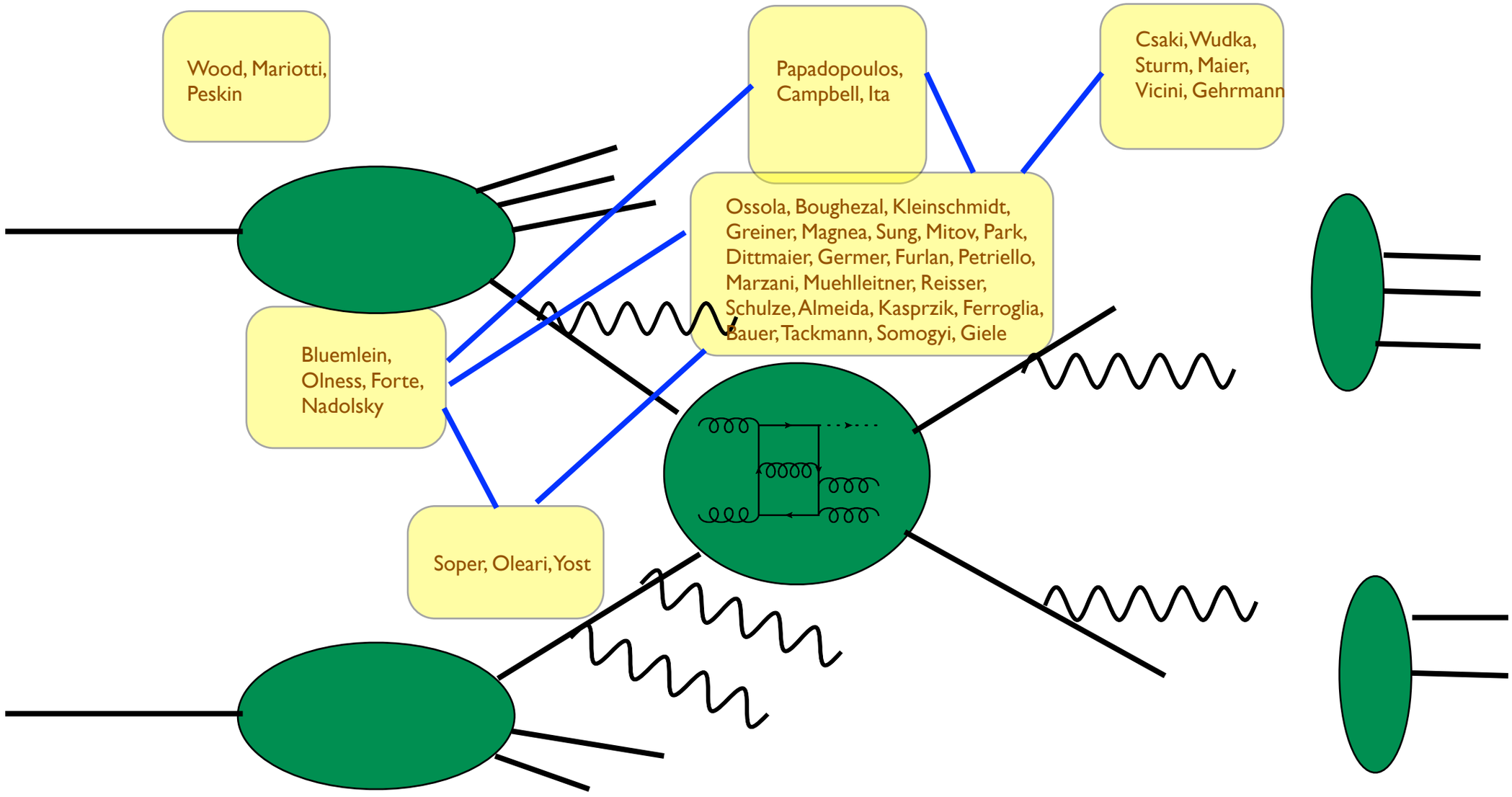
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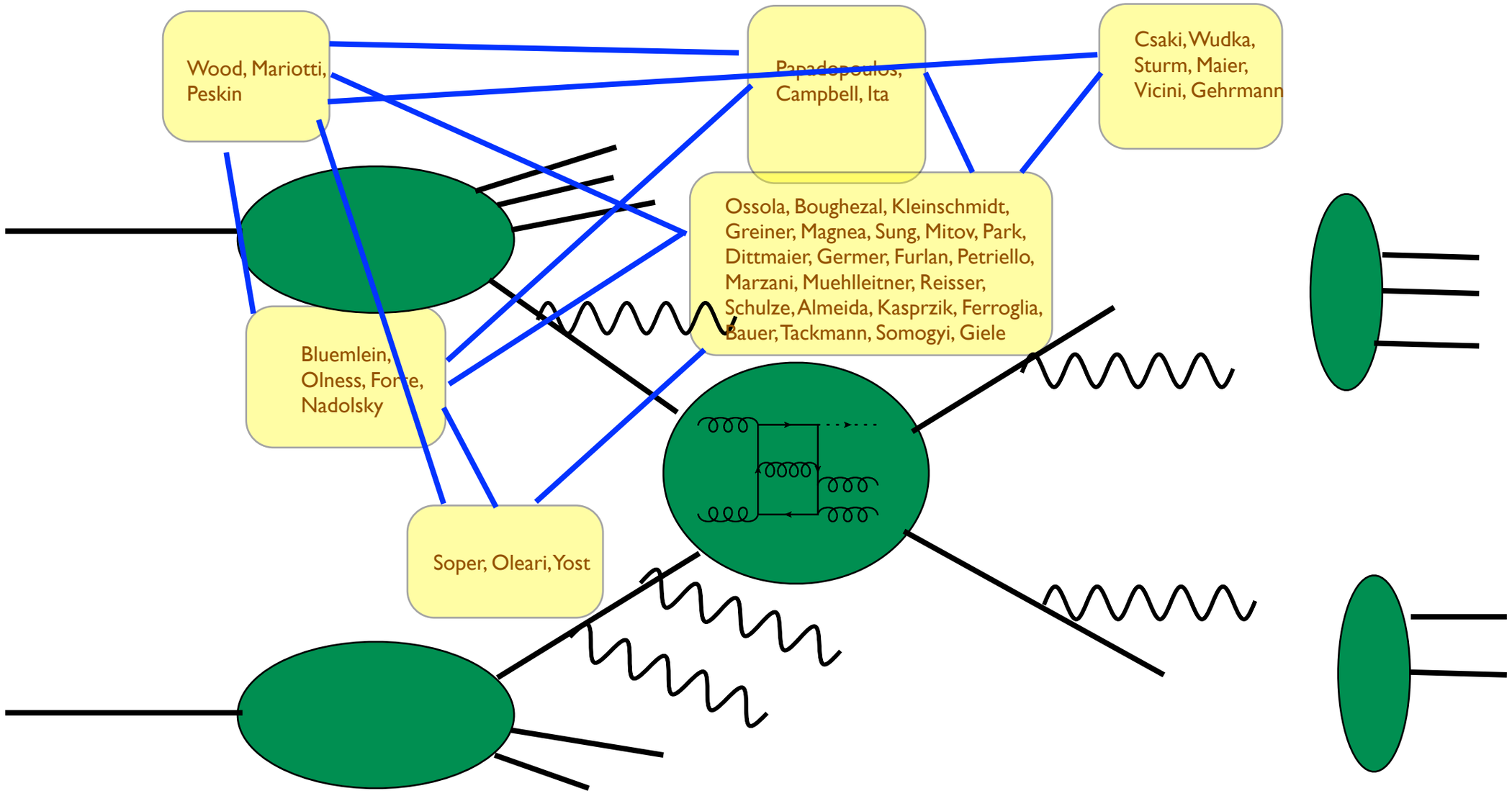
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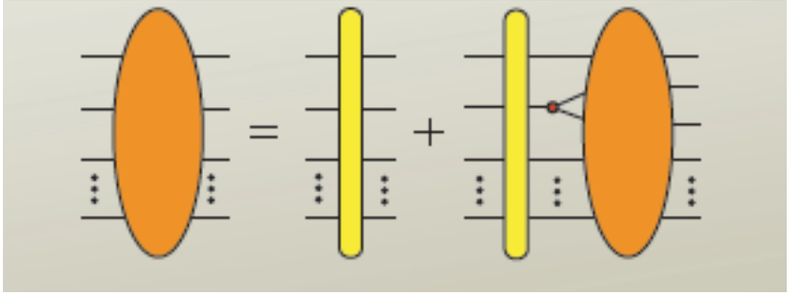
Monte Carlo, parton showers

- Check how well PS reproduces analytic resummation, e.g. pT of Z boson, depending on "shower time"
  - virtuality ordering: yes
  - angular ordering: ok, CS: no, kT: no
- HERWIRI: YFS-exponentation based
  - v2.x this summer
- POWHEG status
  - best of NLO and PS
  - many processes (bosons, heavy quarks, Higgs), soon with jets
  - POWHEG Box
    - ✓ easy inclusion of new processes
  - issue: data too secluded?

Soper

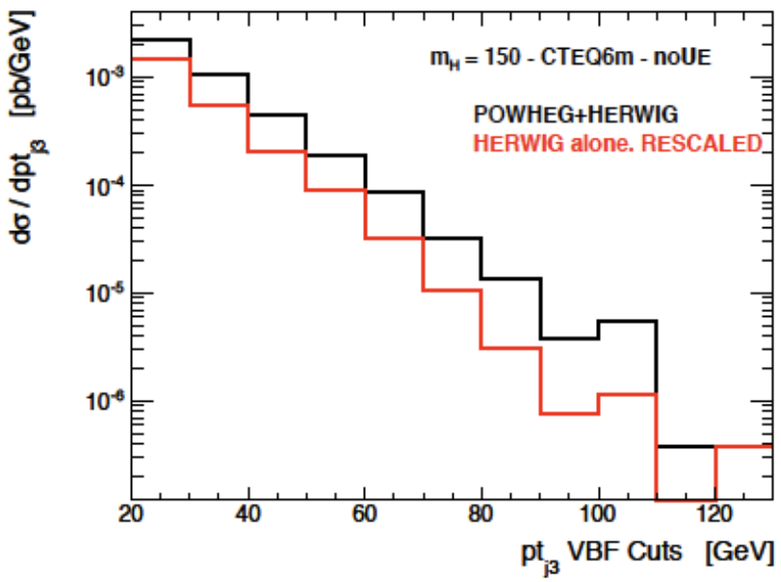
Evolution in shower time



Yost

Oleari

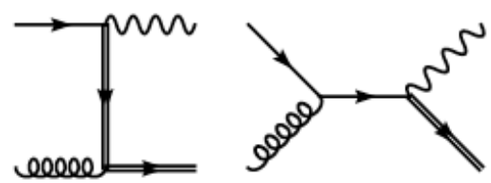
VBF



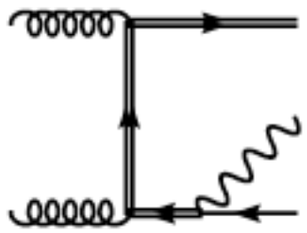
W+t in MC@NLO

Frixione, EL, Maltoni, Motylinski, Webber,White

- In corrections to Wt, interference with much larger tT process
  - due to tT decay



- Define MC subtraction
  - 2 ways, whose difference is interference



- With cuts, allows Wt to exist as separate process to NLO
  - important as signal, and as background (to Higgs production)

Listarchy

- Ruled by NLO wishlist
  - what a marvellous invention
  - so much achieved in so little time
    - ✓ many 2 →4 codes
    - ✓ by multiple groups!
  - new wishes voiced [Wood]
- Challenge
  - experimenters must play with the new toys..
  - .. or at least talk to us
  - public/user friendly codes

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [4,5]; Campbell/Ellis/Zanderighi [6]. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [7]
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [8]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [9,10]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [11] and WWZ by Hankele/Zeppenfeld [12] (see also Binoth/Ossola/Papadopoulos/Pittau [13])
4. $pp \to t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini [14,15] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [16]
5. $pp \to V$+3jets	calculated by the Blackhat/Sherpa [17] and Rocket [18] collaborations
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek [19]
7. $pp \to VVb\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
8. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [20–22]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	$q\bar{q}$ channel calculated by Golem collaboration [23]
NLO calculations added to list in 2009	
10. $pp \to V$+4 jets	top pair production, various new physics signatures
11. $pp \to Wb\bar{b}j$	top, new physics signatures
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
Calculations beyond NLO added in 2007	
13. $gg \to W^*W^*$ $\mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
14. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
15. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
16. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

One loop methods

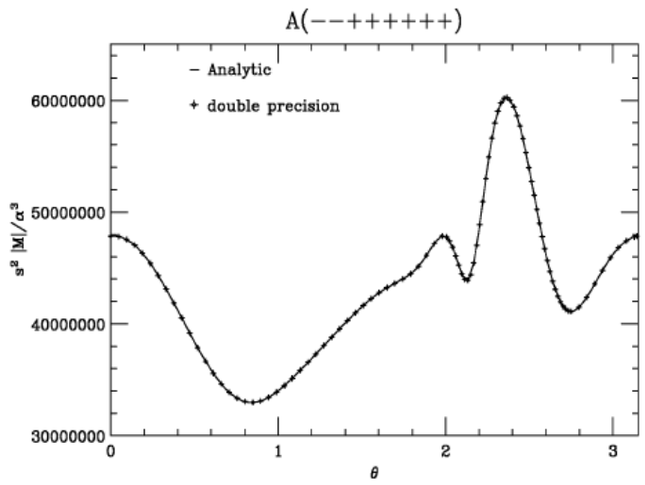
- Golem95: library of one-loop integrals
  - Numerically stable reduction of loop integrals
  - up to six point included, masses (complex) coming
  - upgrade to Golem-2.0 underway
    - ✓ does it all: graphs, reduction, evaluation
- SAMURAI: also for one-loop integrals,
  - OPP method (unitarity, integrand)
  - any number/kind of legs. Masses included
  - tested, public

Kleinschmidt

$$\mathcal{A}^{\{c,\lambda\}}(\{p_j,m_j\}) = \sum_{\{c_i\},\alpha} f^{\{c_i\}}\mathcal{G}_\alpha^{\{\lambda\}}$$

$$\mathcal{G}_\alpha^{\{\lambda\}} = \int \frac{d^Dk}{i\pi^{D/2}}\frac{\mathcal{N}^{\{\lambda\}}}{D_1\dots D_N} = \sum_R \mathcal{N}^{\{\lambda\}}_{\mu_1,\dots,\mu_R} I_N^{\mu_1\dots\mu_R}(\{p_j,m_j\})$$

Ossola



Binoth Les Houches Accord

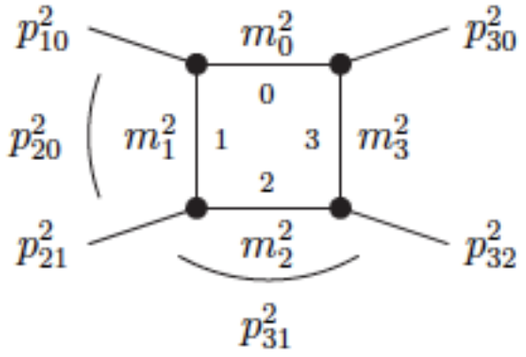
In tribute to Thomas Binoth

- So much of what was shown here came from him
- Proposal by Thomas, at Les Houches 2009:
  - interfacing parton shower to NLO

One loop, methods & results

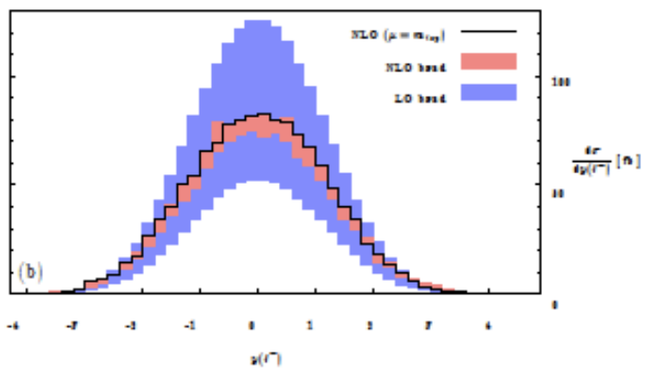
- Complex internal masses
  - necessary when dealing with unstable particles (of which there are a lot)
  - Scalar integral basis required
  - fully general case (with divergences) now done. Dilogs galore.
- New subtraction scheme for Nagy-Soper dipoles
  - less terms, easier matching to PS
  - number of processes checked, matching to PS next year?
- NLO corrections to tT production and decay, and tT plus jet
  - shows use of D-dim unitarity and OPP, also here
  - checked

Dittmaier



Robens

Schulze

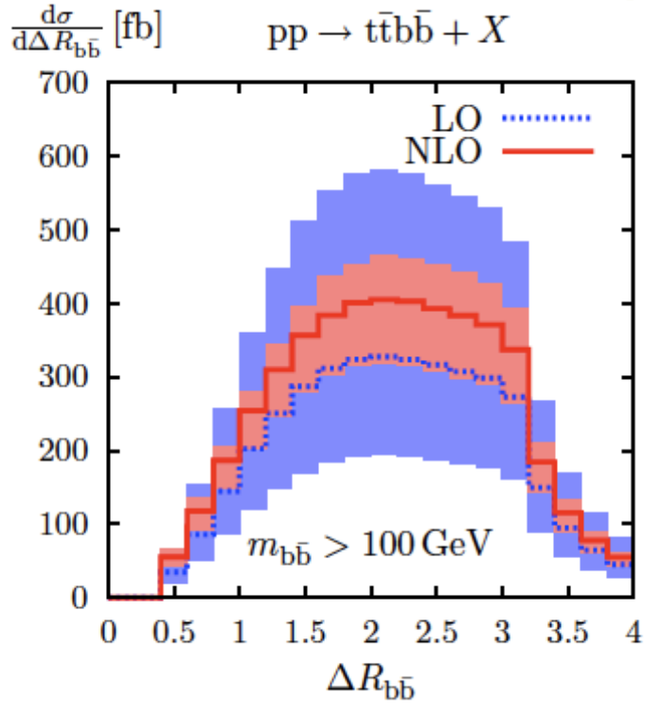


One loop results: 2 → 4

breathtaking alpinism

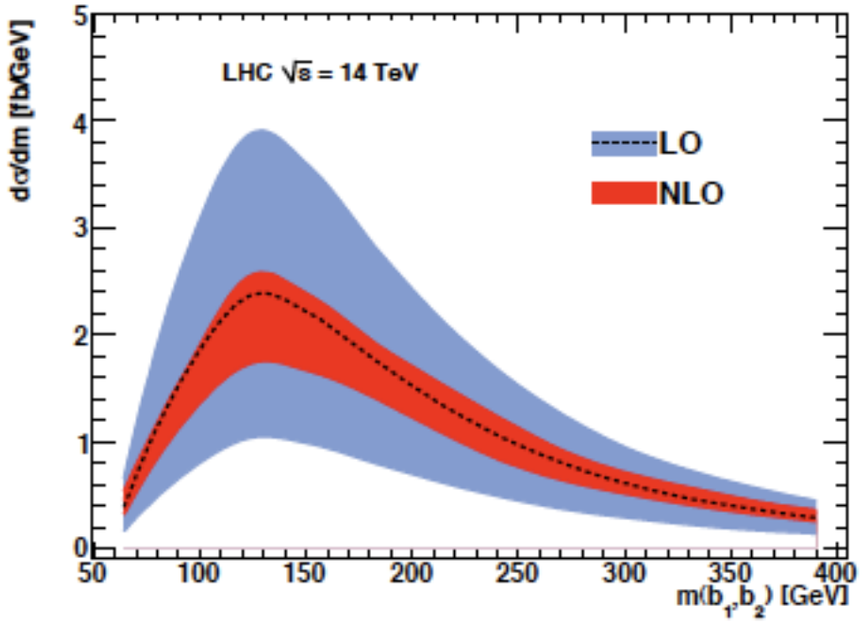
- tTbb to NLO
  - 2 calculations (also Bevilacqua et al); agree
  - key background to ttH (S/B ~0.1)
  - with better scale choice:
    - ✓ K-factor down to 1.25. But bkgd larger than LO by 2.2...

Pozzorini



- Methods used extraordinary arsenal of tools
  - Two independent codes by same team
  - have numerical efficient, stable code; 3 days on 1 CPU
    - ✓ together with Fat-Jets, bring top-Yukawa back in play

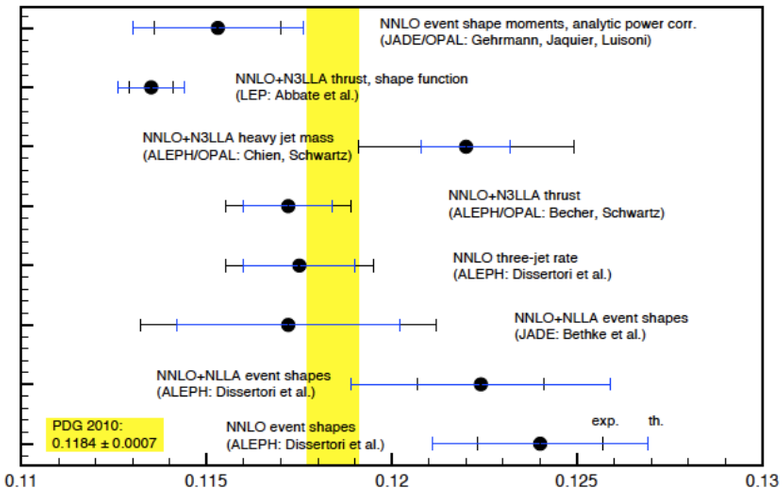
Greiner



- bbbb to NLO
  - on the list. For many BSM signals a background
  - virtual: Golem2.0 (10x faster with Samurai)
    real: MadDipole.

NNLO methods and results

Gehrmann



- NNLO α_s from $e^+e^- \rightarrow$ 3 jets (including event shapes)
  - combined with resummation
  - revisit hadronization, limit factor
- Antenna subtractions for fully differential NNLO cross section for hadron scattering

Boughezal

  - always on horizon, but horizon now approaching
  - some initial state ones now known
    - ✓ tough integrations.
- New set of subtractions

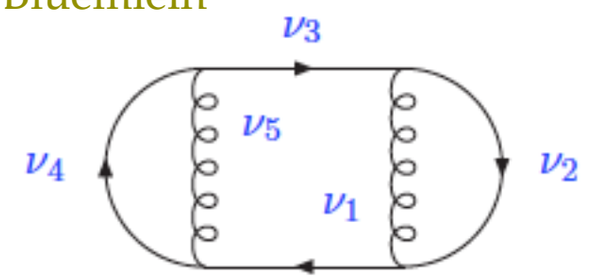
Somogyi

  - +: algorithmic, general, local, efficient -: very hard integrals [but need only once]
  - no hadronic collisions yet

NNLO++, methods and results

- NNLO DIS heavy quark coefficients $Q^2 >> m^2$
  - for gluon, see PDFs, α_s precision
  - using factorization "backwards"
    - ✓ 3-loop massive Operator ME x coeffs
  - general N results @ Loopfest XI?

Bluemlein



- For light quark masses, part is PT
  - needs on-shell scheme, and conversion to MSbar
  - new on-shell scheme + NNLO conversion reduce (part of systematic) error by factor 3

Sturm

- Precise charm and bottom masses
  - from comparing 4-loop current correlators with R(s)
  - $m_c(3\ \text{GeV}) = 986\ (13)\ \text{MeV}$; $m_b(m_b) = 4163\ (16)\ \text{GeV}$

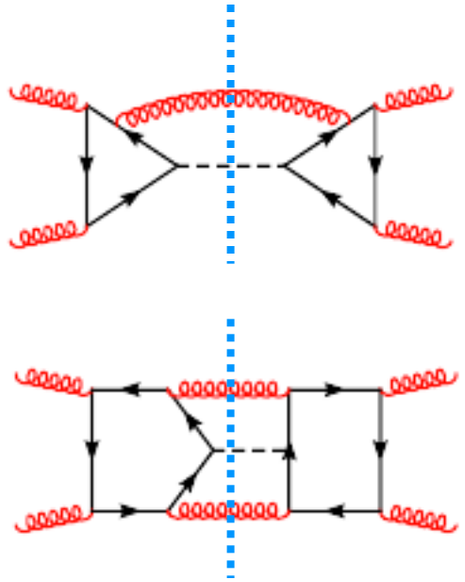
Maier

$$m = \frac{1}{2}\left(\frac{9}{4}Q^2 - \frac{C_n}{M_n^{exp}}\right)^{1/2n}$$

NNLO Higgs production corrections

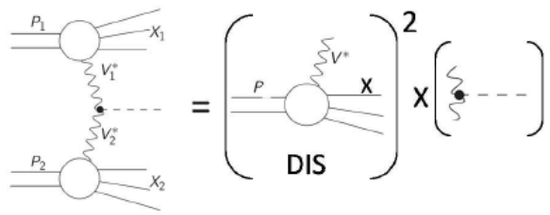
- Gluon fusion, check of heavy top mass limit to NNLO
  - ✓ Use asymptotic expansion in 1/Mt
  - ✓ Match to large s result
  - – phew! Works still to better than 1%!!
  - ✓ Resummation rescues expansion

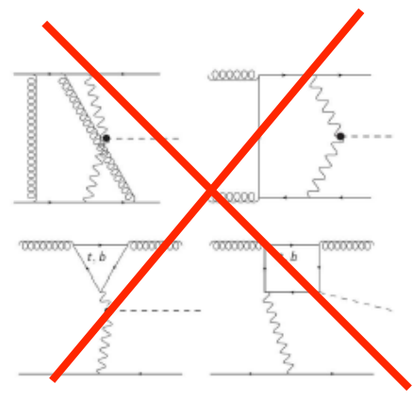
Marzani



- Vector boson fusion cross section to NNLO
  - ✓ at NLO, 5-10 % QCD uncertainty
  - ✓ at NNLO in QCD, in structure function approach, 2% (scale + PDF)
  - ✓ Web interface, just click

Bolzoni

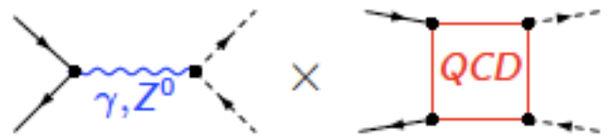




EW corrections

Germer

- to squark/gluino pair production
  - mostly small, but can be important (over 10%)
  - more information in distributions

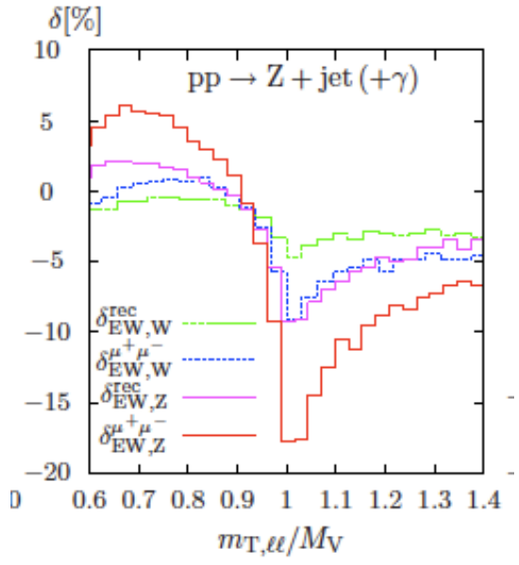


- to neutrino-nucleon (for NuTeV)
  - now fully with muon and charm masses
  - effect on $\sin^2\theta_W$ most of (NuTeV - World A)
    - ✓ PDF's?

Park

- Z+jets at LHC
  - part of Drell-Yan; background to BSM with E_T(miss)
  - full NLO EW corrections, off-shell Z
    - ✓ O(10%) corrections

Kasprzik



Vicini

- combine judiciously with QCD corrections for m_W
  - use experimental template method fully in theory to assess effects of rad. cors. as m_W shifts.

Susy-QCD corrections

- Mostly, not small

  Muehlleitner

  - to gg → H
    - ✓ With squark masses, decoupling holds
  - to h → bb (use LE theorem for vertex diagrams).

    Reisser
    - ✓ Numerical effects: 8%
- 3 loop MSSM corrections

  Steinhauser
  - β function to 3 loops, 300K 3-loop diagrams!!
  - M_h to 3 loops. Result: still few GeV shift in M_h

Effective Field Theory
(better than form factors)

- New Physics, encoded in dim6 operators, and EW precision

  Csaki

  - reduce # from 80 to about 7 "oblique" ones, plus 2 or 3 "coupling" corrections
  - test using random generation of NP models. Works well.

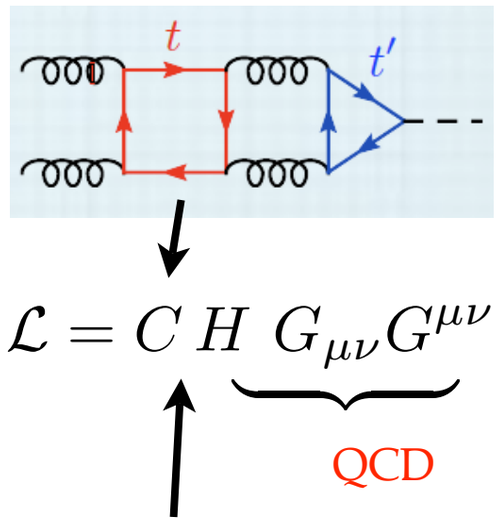
- Dim5,6 neutrino operators

  Wudka

  - difficult to constrain with LHC, LE observables
    - ✓ Red giants and high dim operator
- New Physics in Higgs boson production

  Furlan

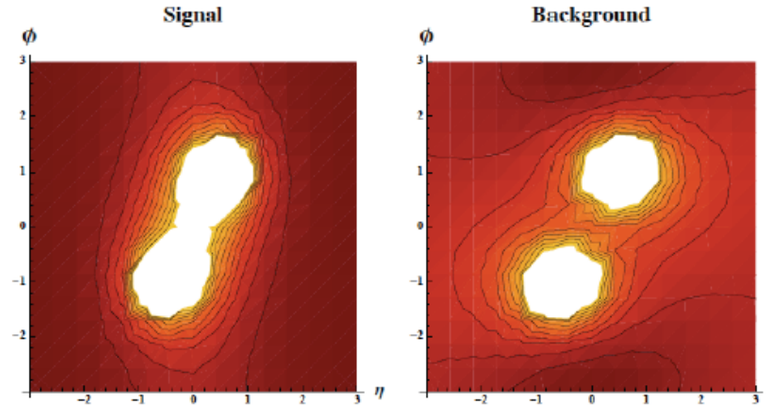
  - promising channel to look
  - generic model included into C, easily included in studies



All orders

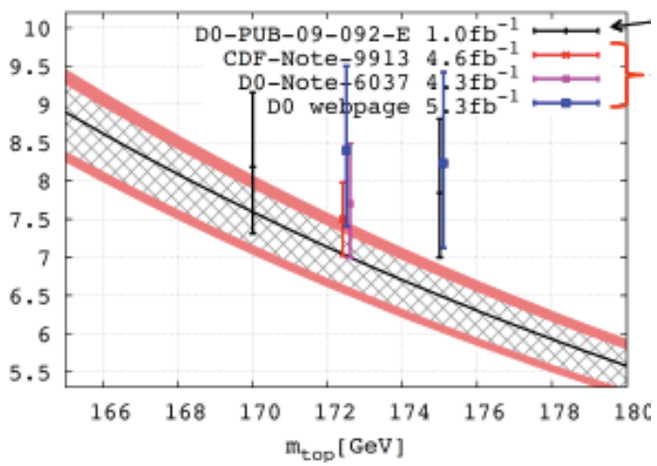
- Can we *fully* understand the IR sensitive structure of gauge theory? Magnea
  - Tools: factorization, dim. reg., eikonal approximation
  - Amplitude (mostly) exponential.
  - Functional dependence of exponent has been surprising.
    - ✓ Severely constrained. Can we know it fully? Looks possible.
    - ✓ Four loops may tell

Sung



- All-order radiative amplitudes sensitive to underlying "antenna".
  - E.g. new particle singlet or octet? Color/energy flow into selected phase space regions may tell
- Massive gauge theory, exponentation ingredients to two-loop (NNLL)
  - Soft function at two-loop. Breaks "loop order scaling"
  - Applied to NNLL σ(tT) [+other items]

Mitov



Beyond the eikonal

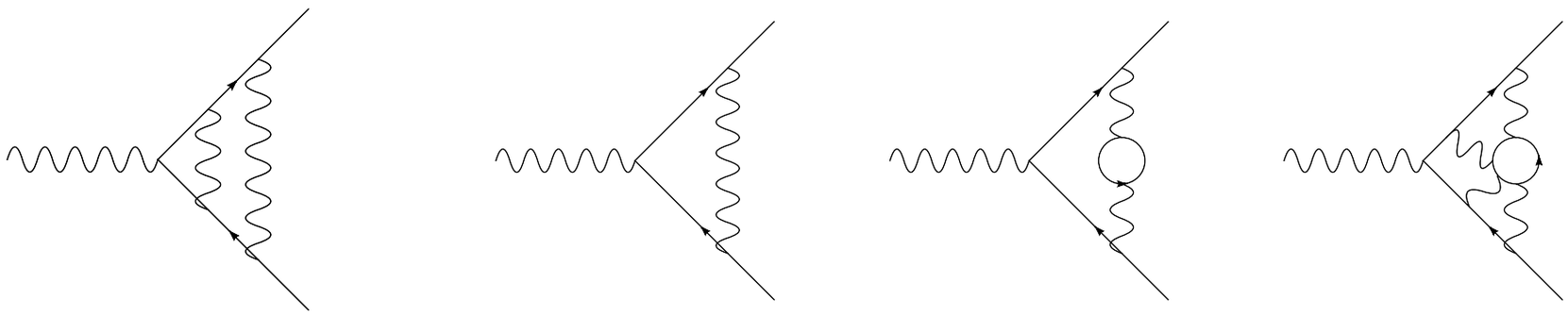
EL, Magnea, Stavenga, White

Amplitude as path integral

$$S(p_1,\ldots,p_n) = \int \mathcal{D}A_s^\mu H(x_1,\ldots,x_n)\, e^{-ip_1x_1} f_1(\infty)\ldots e^{-ip_nx_n} f_n(\infty)\, e^{iS[A_s]}$$

$$f(\infty) = \int_{x(0)=0} \mathcal{D}x\, e^{i\int_0^\infty dt\left(\frac{1}{2}\dot{x}^2+(p_f+\dot{x})\cdot A(x_i+p_ft+x(t))+\frac{i}{2}\partial\cdot A(x_i+p_ft+x)\right)}$$

Eikonal vertices act as sources for gauge bosons along path



Disconnected

Connected

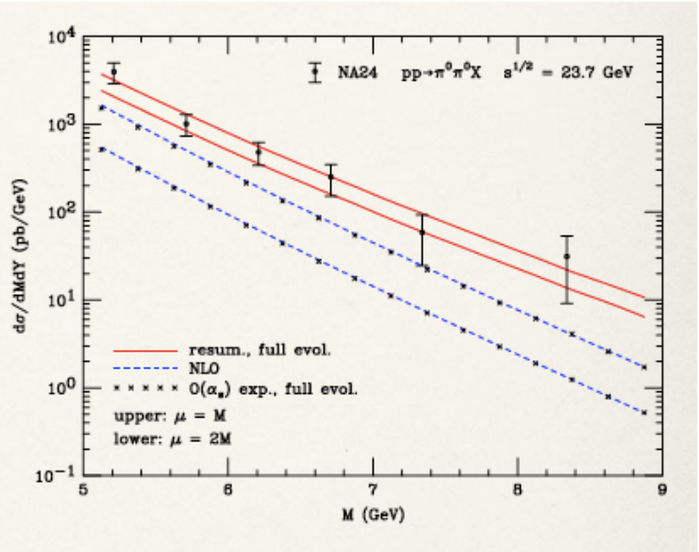
QED: exponentiation now textbook result:
all diagrams = exp (connected diagrams)

QCD: same. Use “replica trick” from Stat Mech.
Exponent = sum of webs: eikonal and new next-to-eikonal ones

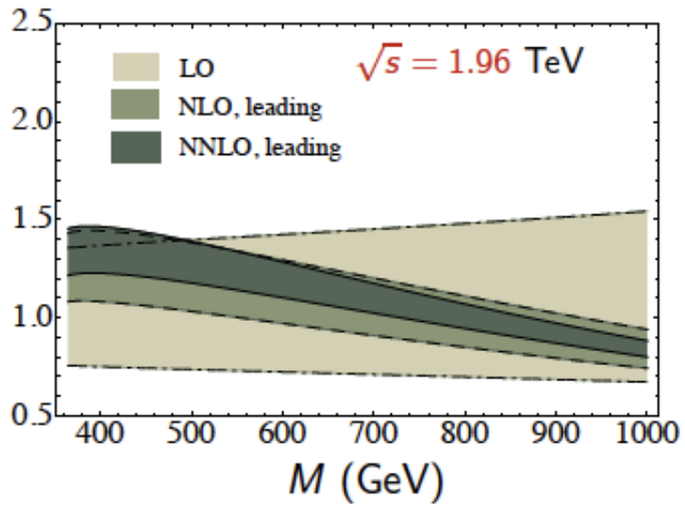
All orders

- NLL threshold resummation for identified hadrons
  - excellent agreement at NLO, 10% resummed
  - when including leading lnN /N , even better
- NNLL threshold resummation, for invariant mass distribution
  - scale dependence much smaller
  - also for NNLO piece of that

Almeida

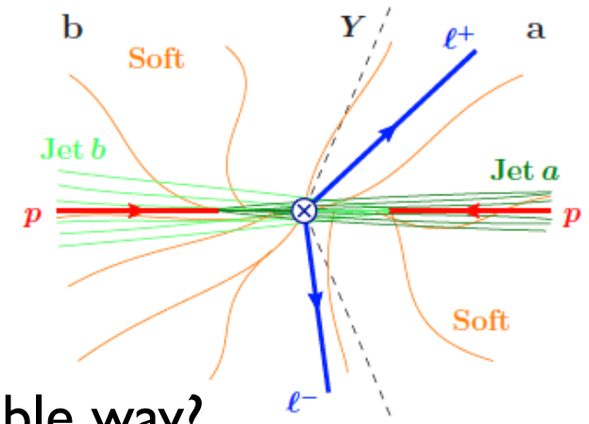


Ferroglia



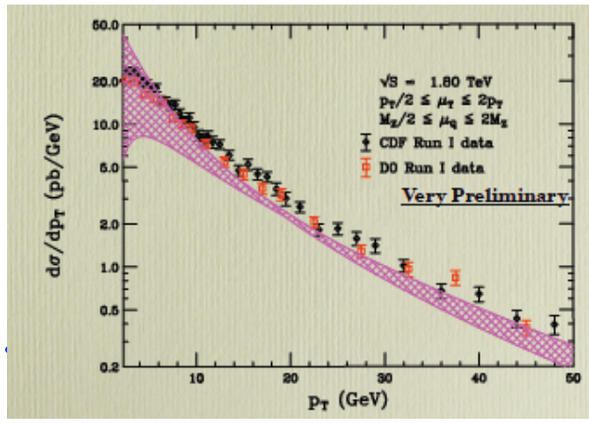
All orders, SCET

Tackmann

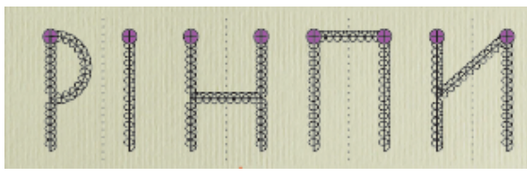


- How to implement jet vetoes in resummable way?
  - beam "thrust". No jets for thrust to one
  - requires factorization with beam functions. Can then resum (NNLL).
- Low pT resummation of H,V
  - Compare with CSS: no Landau pole, easier matching to NLO
  - Application of SCET (with beam functions)
- How to use EFT to derive what the "most convergent" scale choice is
  - for kinematical configurations, not just mass scales

Petriello



Pi H Pi ? Pi N Pi ?

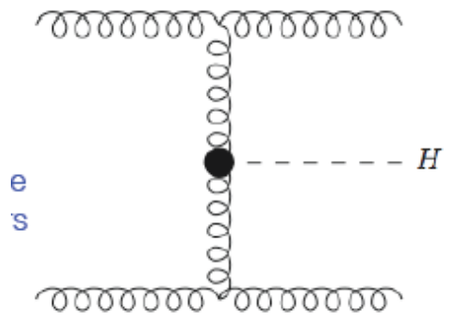


Bauer

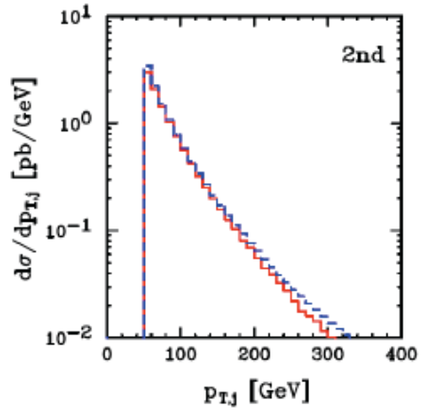
News from the Codes

- MCFM
  - H + 2 jets at NLO now in, using many "tricks"
    - ✓ Speedy (5ms/virt), reduction of H → WW error
  - tT at NLO, with spin correlations
- HelacNLO
  - went way beyond first ambition. Complete package.
  - tTbb, tTjj in. Poised for further speed improvements
- Blackhat
  - first glimpse of W+4j
  - W/Z + up to 3 jet, vs. Tevatron data

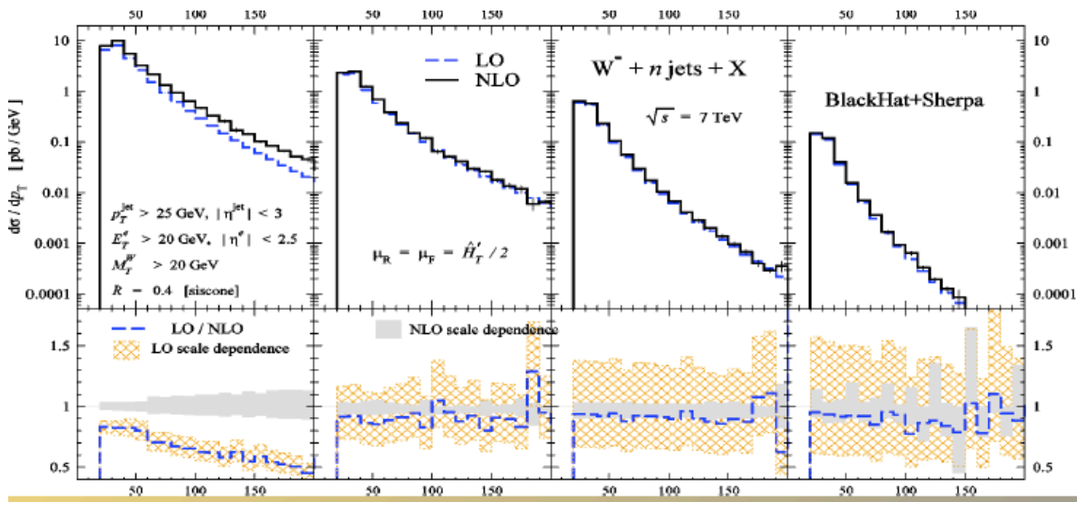
Campbell



Papadopoulos

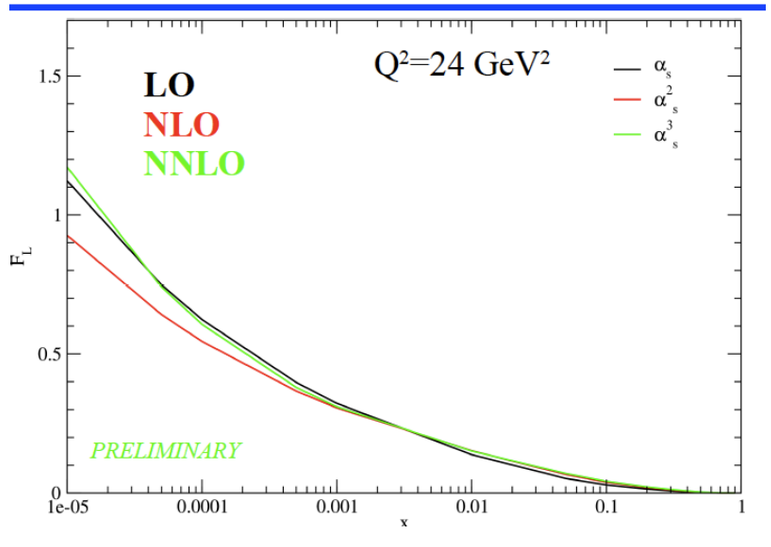


Ita



News from the PDF's

Olness



- Heavy quark PDF's
  - careful, clarifying comparison of schemes ((S)-ACOT, TR, FONLL) performed
  - ACOT being extended to NNLO

Forte

- NNPDF 2.0
  - MC the distribution the space of PDFs. Consistency, stability tests possible.
  - 2.1: Heavy quark mass effects included

Nadolsky

- CTEQ-TEA
  - LO PDF's for parton showers, fit μ and K to mimic NLO
  - PDF's with variable α_s to let its value come out of global fit also

News from Tools

- FORM: @sourceforge this summer — Vermaseren, Kuipers, Vollinga, Pushkina
  - User Forum soon installed
  - New capabilities (factorization of multivariabe polynomials)
  - Future? Use the source!
- GPU's: the future of speed — Giele
  - memory an issue (not easy for FORM eg)

Looking ahead

("Vision thing")

Predictions, a list!

- Loopfest I [BNL]
  - mostly LC
  - NLO parton showers,
  - postscript files
- Loopfest V [SLAC]
  - NLO 2 →3
  - pMC@NLO (!)
  - PDF's standard
- Loopfest IX [SB/BNL]
  - mostly LHC
  - NLO 2 →4, 5
  - LHC NNLO arriving

Loopfest XVIII [BNL/SB]

1. Higgs here, many studies
2. Data driving calculations
3. Fully automated 2 → 18 at NLO. (Point&click) [Feynman diagrams demise exaggerated]
4. Fully differential 2 → 3 at NNLO
5. 2 → 1 at NNNLO, including splitting fns
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More visions?

~~Vision~~ Spectre, absent

Eyjafjallajökull

Quick quiz: explain this name

Wither must we wander?

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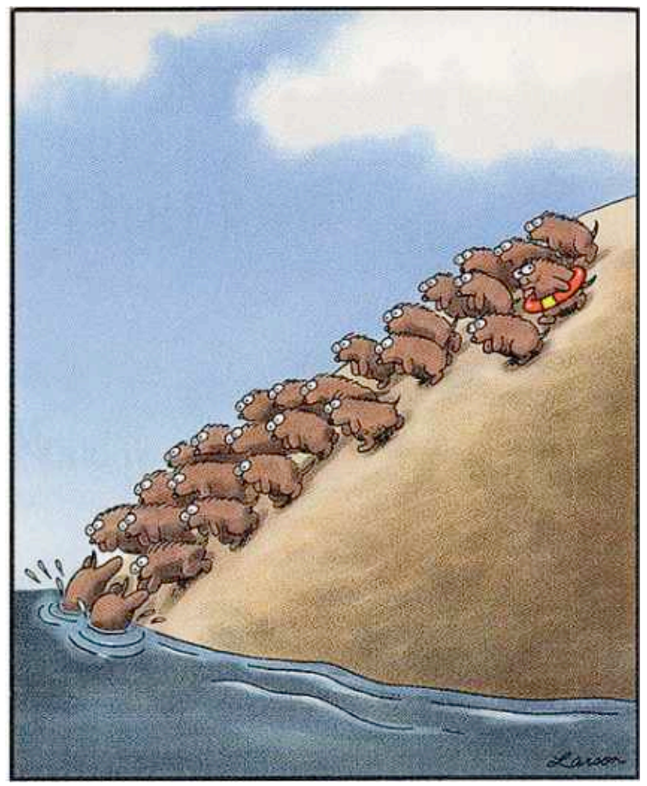
  - ✓ Lemmings?



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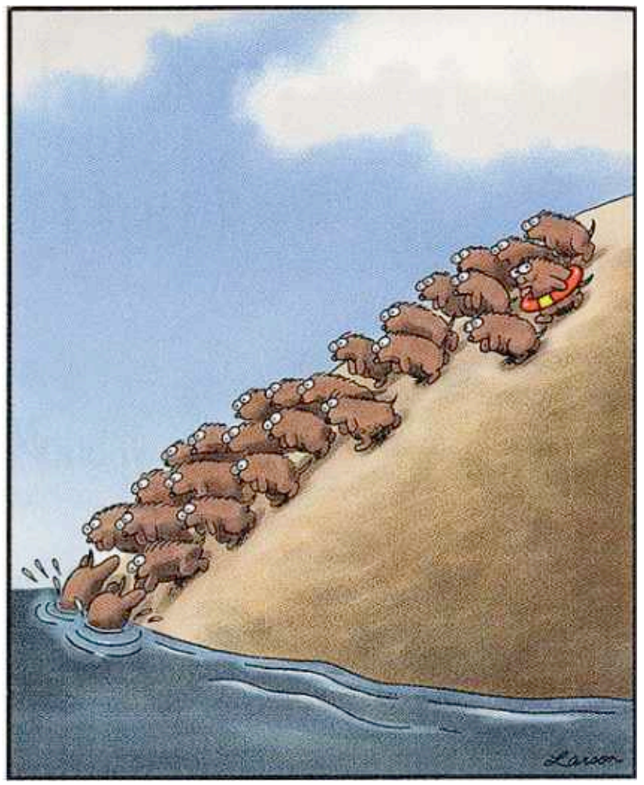

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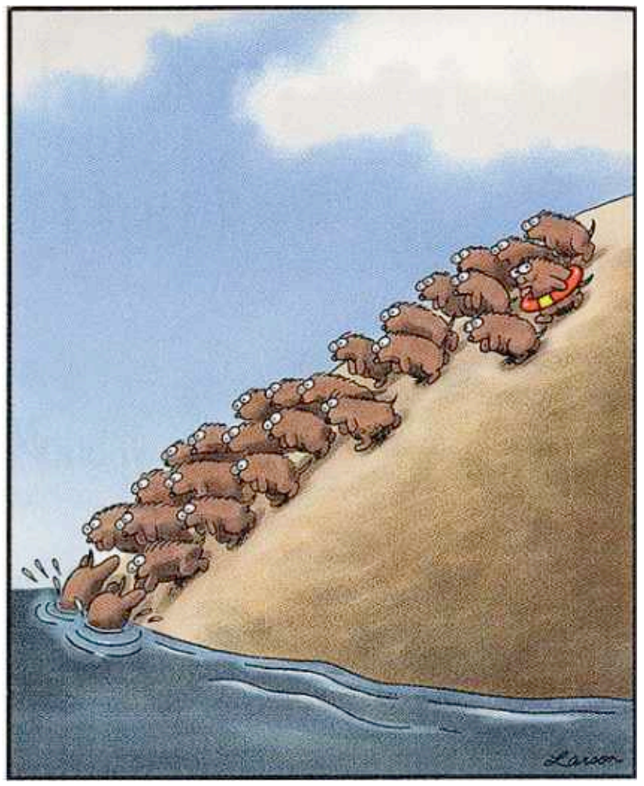
  - ✓ Lemmings?
  - ✓ Charge of the Light Brigade?
- We just *really* want to know what makes the Standard Model tick



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Finally

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  - Vital field: young people, new ideas, variety, competition
- Progress not slowing down with complexity
  - Loopfest X has much to look forward to! (XVIII also)
- A big thanks, from all of us, to the organizers for such a wonderful and stimulating fest
  - ✓ Uli Baur
  - ✓ Sally Dawson
  - ✓ George Sterman
  - ✓ Doreen Wackeroth